Constellation-X Studies of the Solar System

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The X-ray sources in our solar system besides the Sun include Venus, Earth and its Moon, Mars, Jupiter, its Galilean satellites and the Io plasma torus, Saturn, comets, and the heliosphere. Compared to cosmic sources, these are extremely weak X-ray emitters. Nonetheless, these X-rays are an intriguing manifestation of the interaction of these bodies with the magnetized plasma medium in which they are embedded and offer clues to the nature of this interaction. Analyses of these emissions can help advance our understanding of certain basic plasma and plasma-neutral processes within our solar system and, by implication, in extra-solar planetary systems.

Venus, Earth and Moon, and Mars

Most of the X-ray flux observed from Venus, Earth and Moon, and Mars is from fluorescent scattering of solar X-rays, either in the upper atmospheres of these planets or on the lunar surface. While evidence for X-ray radiation from Earth was known over forty years ago (Winckler et al. 1958; Grader et al. 1968), it was 1996 when the first X-ray image of the Earth was obtained (Petrinec et al. 2000). Apollo flights in lunar orbit studied X-ray fluorescence from the Moon; however, it was ROSAT that first imaged the Moon in X-rays (Schmitt et al. 1991). Chandra first detected Venusian and Martian X-rays in 2001 (Dennerl et al. 2002). Simulations of Venusian X-ray emission predict pronounced brightening on the sunward limb (as was detected), and this limb brightening is sensitive to properties of the Venusian atmosphere above 110 km. Thus, X-ray measurements present a way to monitor properties of the Venusian atmosphere. The main difference between the X-ray radiation from Venus and Earth is due to the presence of Earth's pronounced magnetosphere, which provides an additional source of X-ray emission: when electrons, accelerated in the magnetosphere, strike the upper atmosphere, they may emit X-rays by bremsstrahlung. The X-ray intensity of this emission, which occurs at higher energies than fluorescence, is directly related to the precipitated electron flux. Electrons accelerated in the magnetosphere strike the upper atmosphere and emit X-rays, so the X-ray intensity is directly related to the precipitated electron flux. The Martian X-ray properties observed were comparable to Venus due to their similar atmospheres and lack of strong magnetic fields.

Another source of X-ray emission observed from Mars exhibits properties similar to those seen in comets (see below). Also the faint X-ray flux from the direction of the Moon's dark side, originally revealed by ROSAT, has a similar origin: Chandra observations showed that this flux had spectral signatures resembling cometary X-ray spectra (Wargelin et al. 2004), suggesting X-ray emission from the geocorona, an extended cloud of hydrogen around the Earth. Chandra and XMM-Newton (Dennerl 2002) observations of Mars have revealed a faint, extended X-ray halo, and the XMM spectrum of this halo displayed emission lines seen in cometary X-ray spectra. Since Mars' exosphere is, perhaps, a planetary analogue to cometary coma, the mechanism producing cometary X-rays could be operating at Mars. Understanding Mars' exosphere may aid in characterizing the X-ray properties of Earth's geocorona, subsequently revealing how this foreground emission could affect all X-ray observations.

The Jovian and Saturian systems

The Einstein observatory first detected X-rays from Jupiter in 1979 (Metzger et al., 1983), and ROSAT regularly observed Jupiter (see the review by Bhardwaj and Gladstone 2000). While observations from Chandra (Elsner et al. 2005) and XMM-Newton (Branduardi-Raymont et al. 2004) have increased our understanding of its X-ray properties, high-throughput, high-energy resolution observations by Constellation-X will help resolve open questions.

X-ray studies of Jupiter's auroral zones near the north and south poles, where the X-ray emission is most intense, offer a probe of Jupiter's magnetosphere. Spectral analyses of Chandra and XMM-Newton data show that this auroral emission is due to the precipitation of highly ionized oxygen and either sulfur (favored by Chandra) or carbon (favored by XMM) into the polar regions (Horanyi et al. 1988; Cravens et al. 1995, 2003). The ionization states present and the line characteristics would provide information on the electric fields present, thus probing the polar magnetosphere dynamics. Chandra observed ~40-45 minute oscillations in the northern auroral flux observed in December 2000 (Gladstone et al. 2002) that are likely associated with the energetic particle flux in the outer dusk magnetosphere and with quasiperiodic radio bursts from Jupiter (McKibben et al. 1993; MacDowall et al. 1993; Karanikola et al. 2004). More detailed observations of these oscillations and the conditions under which they appear would further constrain the dynamics of Jupiter's polar magnetosphere.

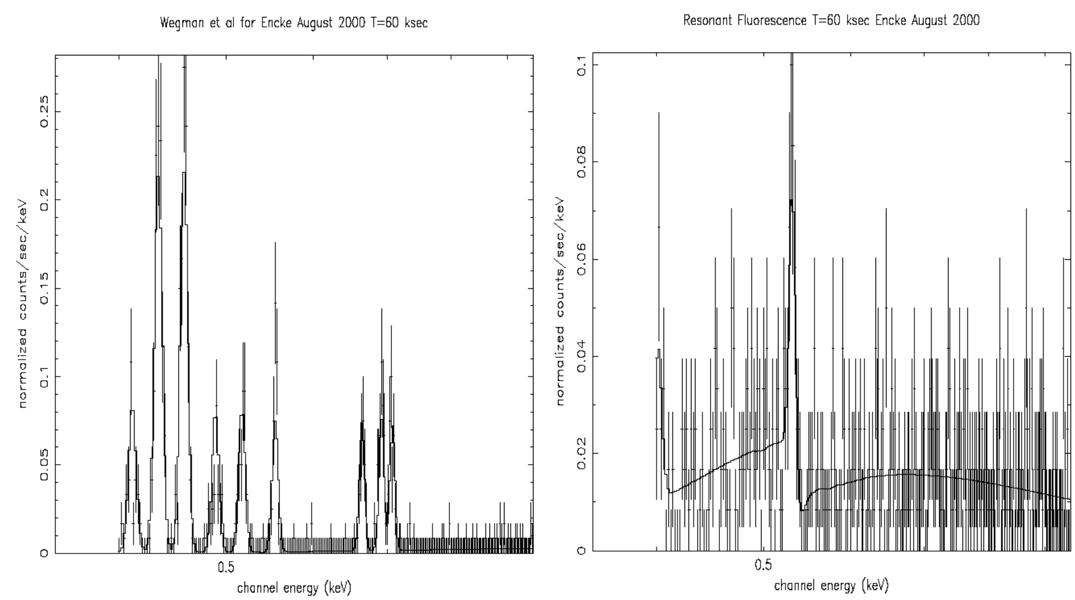

Figure 1:

Away from the polar regions, Jupiter's X-ray emission appears to be a spatially featureless disk illuminated by solar X-rays (Elsner et al. 2004; Bhardwaj et al. 2005a). Analysis of Chandra spectra is underway to test a model of elastic X-ray scattering by atmospheric neutrals and carbon K-shell fluorescent emission from methane molecules below the Jovian homopause (Maurellis et al. 2000). Regardless of the results, Constellation-X observations will refine models and show deviations from this model, for example due to energetic ions precipitating into the atmosphere from the radiation belts (Gehrels and Stone 1983; Waite et al 1997; Gladstone et al. 1998).

Chandra observations in November 1999 and December 2000 discovered faint X-ray emission from the Io plasma torus and Io, Europa, and possibly Ganymede (Elsner et al. 2002). While the origin of the X-ray emission from the torus in not clear, the emission from the Galilean moons is almost certainly due to bombardment of their surfaces by energetic hydrogen, oxygen, and sulfur atoms and ions. These objects are very faint, so high-throughput, low-background, high-energy resolution observations are necessary to further understanding these emissions.

Saturn was marginally detected by ROSAT in April 1992 (Ness and Schmitt 2000); however, the first unambiguous detections came from Chandra and XMM (Ness et al. 2004a,b). In January 2004, Chandra observations found variations in the averaged X-ray flux of a factor of ~4 over one week (Bhardwaj et al. 2005b). These variations appeared closely tied to the incident solar X-ray flux. In addition, on timescales of ~0.5 hour, an X-ray "flare" from Saturn was closely linked to the eruption of solar X-ray flare. The January 2004 observations provided the first glimpse at X-ray emission from the south polar cap and an emission line probably due to oxygen Kα fluorescence from the rings. Saturn is a faint X-ray source, and detailed investigation of its X-ray properties requires the high-throughput and high-energy resolution provided by Constellation-X.

Comets

The 1996 discovery of strong X-ray emission from comet C/1996 B2 (Hyakutake) by ROSAT (Lisse et al. 1996) was surprising, since cometary atmospheres are known to be cold, with characteristic temperatures between 10 and 1000 K. Comets are moderately weak X-ray emitters, with the amount of energy emitted in X-rays equivalent to ~10^{-4} times the energy delivered to a comet from the Sun due to photon insulation and solar wind impact (Lisse et al. 2001). Chandra found that the soft X-ray spectra from comet C/1999 S4 (LINEAR) (Lisse et al. 2001) was dominated by line emission, not by continuum. Line emission is also found in XMM spectra of comet C/1999 T1 (McNaught-Hartley) and, more recently, in Chandra spectra of C/2000 WM1 (LINEAR) and C/2002 Ikeya-Zhang (Dennerl et al. 2005).

Solar wind minor ions readily undergo charge transfer (or exchange) reactions (Phaneuf *et al.* 1982, Dijkamp *et al.* 1985, Gilbody 1986, Janev *et al.* 1988, Wu *et al.* 1988) when they are within ~ 1 nm of a neutral atomic species. Model charge exchange X-ray spectra are in good agreement with the low resolution X-ray spectra from comets, and the line centers of the high resolution spectra have been successfully predicted using charge exchange theory (Lisse *et al.* 1999, 2001; Krasnopolsky and Mumma 2001; Weaver *et al.* 2002).

The best spectrum available (Chandra ACIS-S) of cometary X-ray emission is limited in energy resolution and spatial quality. Due to the extended nature of comets, both Chandra and XMM data require complex interpretation, while suffering from low spectrometer throughput. The high quantum efficiency and energy resolution of the Constellation-X mirocalorimeter removes such problems from Constellation-X observations. In addition, the Constellation-X spectrometer will be sensitive to the forest of lines predicted by solar charge exchange models (e.g., OVIII, OVII, NVIII, NVI and CVII). Constellation-X will also offer sufficient resolution (≥ 70eV; as shown by Wegmann et al. 1998, and Kharchenko and Dalgarno 2000) to distinguish between emission due to solar wind charge transfer and bremsstrahlung.

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